Photomultiplier and filter combinations for the detection of relatively long wavelength (λ>600 nm) luminescence emissions from feldspar

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***Abstract** : We describe our efforts to detect IR-stimulated (λ ~ 833nm) orange-red emission ($\lambda_{emission}$ = 600-750 nm) luminescence from potassium feldspars for dating applications. The aim here is to provide basic information about the detection of orange-red IRSL, as an alternative to conventional IRSL approaches which typically exploits portions of the IR-stimulated UV-blue ($\lambda_{emission}$ < 600 nm) luminescence. We describe modifications to a standard Risø reader, which make it possible to detect orange-red IRSL. Modification consist of various optical filter combinations and extended range, cooled photomultipliers. The use of a modified Electron Tubes D716A "green" bialkaline PMT (green tube) provides a greater quantum efficiency (0.1- ~5% QE) in the wavelength range 600-700 nm than the traditionally used 9635 bialkaline tube (1-negligible% QE @ 600-700 nm). An extended S20 9650 PMT (red tube) provides a greater quantum efficiency (~7-12% QE) in the wavelength range 600-700 nm than both the 9635 and D716A. A substantial disadvantage of using an extended S20 tube is its relatively high quantum efficiency (2.5%) at 830 nm. Filter combinations were examined by both a UV-visible spectrometer and direct measurement of filter/PMT transmission characteristics. Our data suggest that optimal PMT/filter combinations consist of using the green PMT + two FR 400S + BG 39 and either OG 590 or RG 665 for detection of either a broad orange-red (λ ~ 600-720 nm) or far red (λ ~ 670-720 nm), respectively. The green PMT and an Omega 625DF 50 filter is the optimal combination for orange-near red (600-660 nm) emission.*

Introduction

There are potential advantages in using feldspars for luminescence dating of geological and archaeological deposits. These include, the potential for dating over a wide time range; the relatively high luminescence sensitivity to dose; ease of light collection (relating to the wide separation of stimulation and emission bands in conventional IRSL methods); and the significant internal dose of K-feldspars in many cases reducing the uncertainty in measurements of dose rate (Duller, 1997; Fattahi and Stokes, 2001). Wintle (1973) was the first to used feldspar as a natural integrated dosimeter. She observed significant age underestimation and attributed it to the phenomenon of "anomalous fading", where the observed signal stability is far lower than that predicted from kinetic analyses.

Anomalous fading has significantly hindered the use of feldspars in luminescence dating through the loss of stored charge (Visocekas and Zink, 1999; Huntley and Lamothe, 2001). This has resulted in severe age underestimations in many dating applications and a number of approaches have been proposed to circumvent this effect (For review see Fattahi and Stokes, 2002a). One of these approaches is to look for a non-fading signal. Zink and Visocekas (1997) reported that two TL emission bands in feldspar, one in the blue range and another in the far-red, could be separated, below and above 600 nm (Figure 1). The two bands exhibited similar trap activation energies, dose variation and bleaching characteristics, but different in terms of their kinetic and glow peak temperatures. In particular, the red emission band appeared to be unaffected by anomalous fading, and was therefore considered more suitable for dating (Zink and Visocekas, 1997). Zink and Visocekas (1997) successfully dated three feldspars of volcanic origin using the far-red TL emission alone with an additive-dose protocol.

Red TL of feldspar is optically bleachable (e.g., Bos et al., 1994; Prescott et al., 1994; Zink and Visocekas, 1997). Bos et al. (1994) reported a more intense red (at λ ~ 730 nm) than blue emission in oligoclase. They showed that artificially irradiated oligoclase was bleachable, and that the bleaching efficiency of both the blue and red emissions increased with decreasing wavelength. While the sample remained unbleached at wavelengths between 703-800 nm. However, they made no study of the effect of stimulating wavelengths exceeding 800 nm, the wavelengths currently used for IRSL. Prescott et al. (1994) reported that sunlight bleaches red emissions (>650 nm) of TL in some feldspars. Zink and Visocekas (1997) observed that the shorter sunlight wavelengths, around 350-400 nm, showed a higher bleaching efficiency with similar bleaching results in both bands.

None of the above workers explored the effect of IR (λ > c. 800nm) exposure on red luminescence emissions. However, since there is sufficient information on the similarity of trapping centres involved in the blue and red emissions (e.g., Bos et al., 1994; Zink and Visocekas, 1997), it can be assumed that IRSL using feldspar's red emissions may be useful for dating applications. Optically-stimulated red luminescence (including visible and IR stimulation) could provide methods for the exploitation of feldspars in dating applications provided that the technological problems in its detection, including the effect of black body radiation and fluorescence, can be overcome.

Given its potential to circumvent anomalous fading, we consider the development of a suitable detection system and the testing of IR stimulated red emission to be a key priority in luminescence dating and one which we have begun to evaluate. As with conventional OSL of quartz and IRSL of feldspars, practical advantages in exploiting anti-Stokes radiation encouraged us, in combination with the well-known feldspar stimulation IR resonance, to first consider the use of IR stimulation wavelengths to detect a red emission. As the initial TL investigations in this area (e.g., Zink and Visocekas, 1997) studied orange-red TL (λ c. 600 - 750 nm) to overcome anomalous fading, we decided to similarly investigate an orange-red IRSL signal with same wavelength range.

This paper is a companion of another paper (Fattahi and Stokes, 2002b) which presents the first contribution for exploring the suitability of the orange-red IRSL of feldspar for dating applications.

Our aim here is to describe our attempts to assemble and test apparatus to detect orange-red IRSL and TL from feldspar, including an overview of the photomultiplier and filter combinations which we have tested.

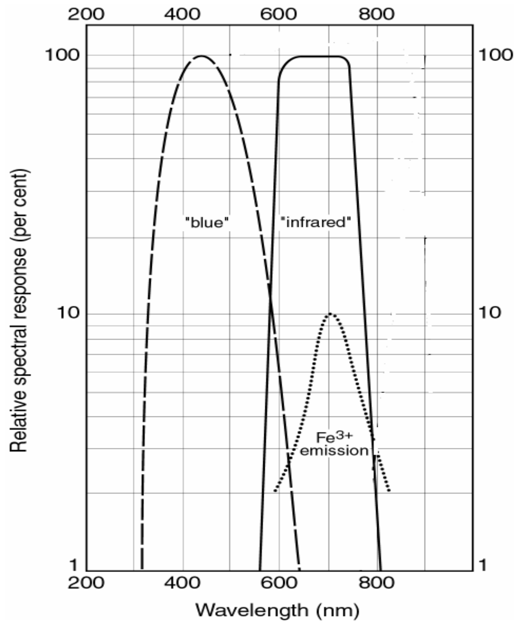

Figure 1.

Blue and IR band for feldspar (modified from Zink and Visocekas, 1997). Continuous line: normalized spectral responses of the arrangements for detection and filtering of the two TL emission bands; IR, with an AsGa photocathode (C 31034 PMT), and two filters (Schott OG 590 + Corion LS 750); Blue with a bialkali photocathode (EMI 9924 PMT) and a filter (Schott BG 18). Short-dashed line: Fe^{3+} emission in feldspar.

2. The photo-detection system

Photomultiplier tubes (PMT)

To increase the detection efficiency of red signal and decrease the IR background, a suitable photo detection system must be employed that detects red wavelengths between 600-750 nm, and cuts the IR wavelengths greater than 750 nm. There is no ideal PMT with high quantum efficiency at red emission and 0% QE at other wavelengths. Figure 2a shows the spectral response and quantum efficiency of selected widely available photomultiplier tubes.

While bialkaline PMTs, such as the Electron Tubes 9635Q "blue" tube, are highly suited to the detecting of UV-blue emission, they have poor quantum efficiency at longer wavelengths (Figure 2a). As can be seen in Figure 2a, the 9635Q photocathode should not be sensitive to wavelengths greater than c. 650 nm, which potentially is a great advantage for

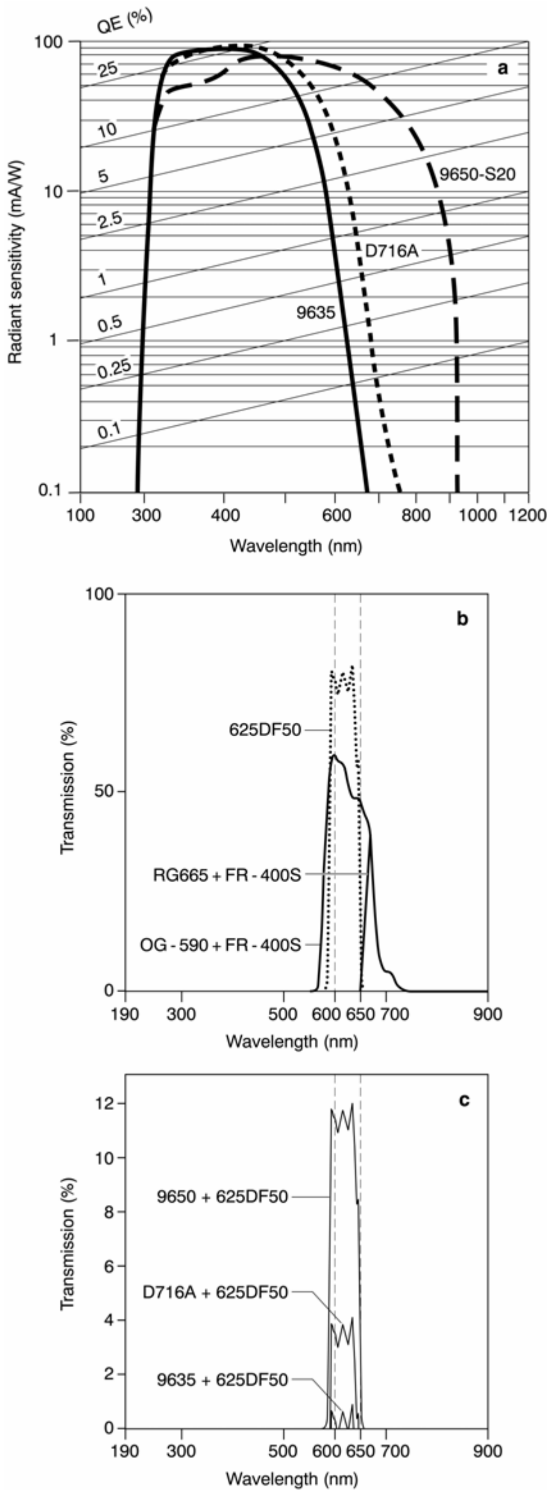

Figure 2.
The expected red detection window through different PMTs and filters. (a) PMT quantum efficiencies. (b) The transmission characteristics of Omega 625 DF50 filter and either a combinations of an FR 400S and either OG590 or RG 665 filters. (c) Transmission window resulting from a combination of Omega 625 DF50 and the PMTs.

preventing background produced in the IR range. However, in empirical tests we have found that this PMT is significantly sensitive to IR, which may be due to photosensitivity in the coating of the first dynode (Aitken, 1998). The limited IR sensitivity of a 9635Q type PMT has actually been noted and exploited by other workers (e.g. Miallier et al., 1991).

The use of an extended S20 9650 PMT (red tube) provides a greater quantum efficiency (15% QE) in the wavelength range 600-700 nm than the traditionally used 9635 bialkaline tube (0.1% QE @ 600-700 nm). This red high sensitivity tube is particularly suitable for the detection of red thermoluminescence and has been successfully employed in RTL studies (Fattahi and Stokes, 2000a, b). A substantial disadvantage of using such an extended S20 tube is its relatively high quantum efficiency (2.5%) at 830 nm (the IR laser diode peak emission wavelength in our RISO reader [Boetter-Jensen et al., 2000]) and high dark count at room temperature (c. 2,000 c.s^{-1}). While this thermally-generated dark count can be reduced by an order of magnitude by active cooling down to c. -15°C (Fattahi and Stokes 2000a: Figure 3), the sensitivity of the tubes at the IR stimulation wavelength remains problematic. There are two obvious alternative approaches. Firstly, to use an IR laser source with a wavelength peak at greater wavelength (i.e. $\lambda > 950$ nm). Such a wavelength is within the IR stimulation spectrum of feldspars (Spooner and Franks, 1990; Duller, 1997), but should not be detected by an S20 9650 PMT (Figure 2). However, it should be noted that Figure 2a shows almost no sensitivity for blue PMT at 830 nm, while empirical tests have demonstrated this not to be the case. On this basis some IR sensitivity might be anticipated for the red PMT even at 1000 nm. A second option would be to exploit a PMT with a spectral response greater than that of the "blue" tube, but less extended than the "red" S20 tube. This second option was pursued and a "green" PMT (EMI D716A) was tested. The advantages and limitations of these three available PMTs that can be used for orange-red IRSL studies are summarized in Table 1.

We have attached a D716A PMT to a Risø model TA-15a automated TL/OSL reader using a flange that locates the D716A tube above the standard Risø OSL/IRSL collar. This arrangement allows routine operation of the Risø reader while either the 'red' or 'green' 'blue' tube is mounted. This flange is similar to the flange used for locating the S20 PMT above the Risø reader (Fattahi and Stokes, 2000a, Figure 2) but with reduced height (16 mm in comparison to 43 mm for the original collar which was designed to incorporate an optical fiber input), which increases the photon yield.

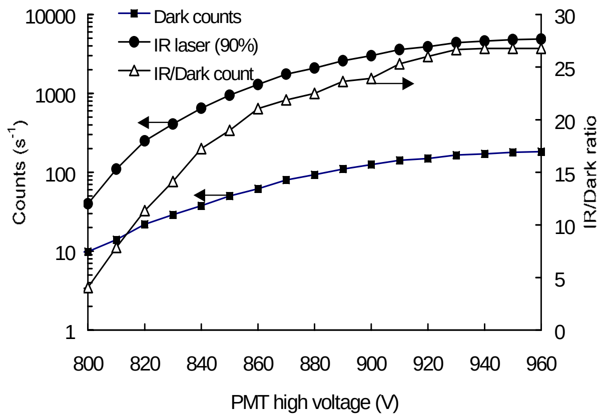

Figure 3.
The voltage dependent response of EMI bialkaline D716A "green" tube. A blank stainless steel disk was used to measure the reflection of IR.

Similarly to the S-20 PMT, a disadvantage of the D716A PMT is its relatively high dark count at room temperature (c. 2,000 c.s^{-1}). This thermally-generated dark count can be reduced by an order of magnitude to levels comparable to that of a 9635 bialkali tube by active cooling down to ~ -20°C. For this purpose we use the same Thermoelectric Refrigerated Chamber as described earlier. Maximum cooling (~Δ40°C) can be achieved within 1 hour of switching on, while the warm-up cycle takes on the order of 3 hours. We tested the voltage response of the D716A PMT and found its response characteristics and optimised voltage to be similar to that for conventionally used 'blue' tubes (Figure 3).

Optical filters

In considering filter combinations for orange and red emission IRSL measurements, we attempted initially to maximize luminescence transmission of 600-750 nm, while minimizing passage of other photons. The main reason for choosing 600 nm as the lower wavelength bound of the transmission window is the success of Zink and Visocekas (1997) who overcome anomalous fading in TL from feldspar using a similar transmission window and a Schott OG590 orange-red transmission filter. In subsequent experiments we have attempted to identify filter combinations, which isolate far red (i.e. λ >665 nm) emissions. We have tested a range of filter combinations by measuring transmission windows using a UV-IR spectrophotometer. Six heat (IR) rejection filters were incorporated in our tests (Figure 4a). The filters tested consist of both those, which are widely available and in use in luminescence laboratories, and a series of relatively new multilayer varieties. The Hoya HA-3 and Schott BG-39 are widely employed in TL and OSL applications for long cut filtering and heat rejection (Aitken, 1998). We additionally tested a multi-layer laminated Corion FR-400S, a Delta SWP 685, and an Omega 750 SP interference filter (Figure 4). There are ranges of long pass filters capable of restricting wavelengths shorter than c. 600nm. Of these we have chosen to examine the characteristics of the Schott OG-590 [the filter employed by Zink and Visocekas (1997)] and Schott RG-665 filters. Additionally, a band pass Omega 625DF50 filter has been tested to observe orange-near red (λ c. 600-660 nm) emissions (Figure 2b).

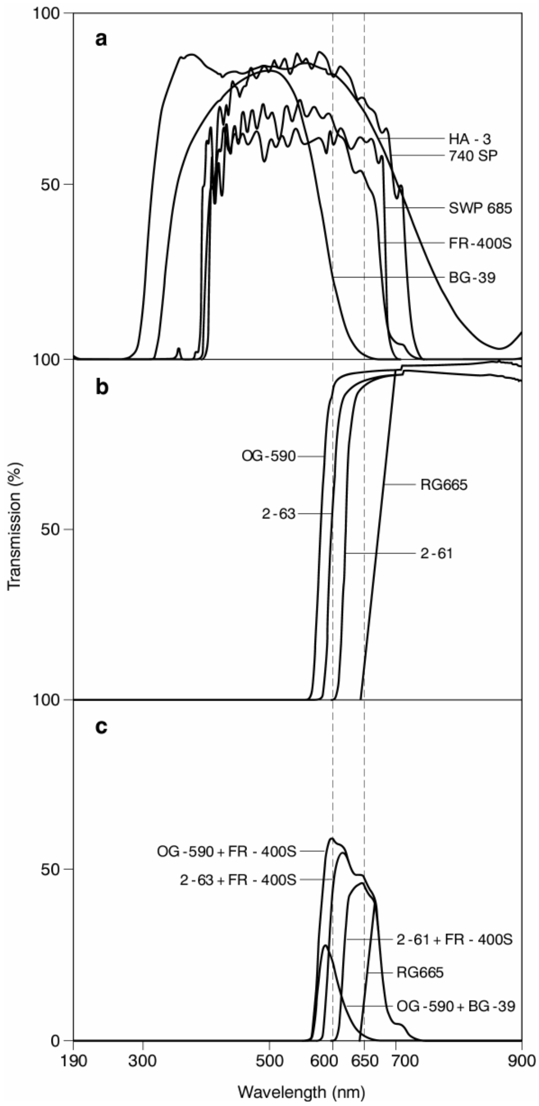

Figure 4.
Transmission characteristics of selected (a) long cut filters, (b) short cut filters and (c) the combination of some long and short cut filters.Spectrophotometer analysis

All spectrophotometer measurements were undertaken at room temperature using a Shimadzu UV-IR spectrophotometer model P/N 204-58000. Examination of the long cut filters characteristics reveals strong contrasts (Table 2). While the HA-3 filter offers a broad transmission window passing from UV to red at levels in excess of 60%, its high (20%) transmission in to the IR renders it of limited utility for RTL and orange-red IRSL studies. Detailed examination of the Schott BG-39; Corion FR 400S; Delta SWP BL 685 and Omega 625DF50 transmission characteristics reveal minor but important IR pass windows at around 760-900 nm (Table 2). While the high signal pass levels are advantageous in red luminescence studies, these IR pass windows significantly complicate sample stimulation with IR.

Of the filters tested the BG-39, Corion FR 400S, Delta SWP BL 685 and Omega 625DF50 offer the best (i.e., lowest) IR transmission characteristics between 760-900 nm. However, the BG-39 transmits only c. 20% of that passed by the FR-400S in the wavelength region 600-700 nm. The Omega 625DF50 transmits 80% of the signal between 600-640 nm and c. 60% transmission between 640-660 nm. Omega 740 SD offers the highest transmission between 600-700 nm (>60%), but it is an inefficient heat rejection filter with ~1.1% transmission between 890-900 nm (Table 2). None of the IR cut filters examined fully cuts unwanted low energy photons (>750 nm) and pass all signals between 600-750 nm. As an alternative, we have explored combinations of long cut filters.

The results for selected filter combinations are summarized in Figure 4. Of these, the combination of FR-400S plus OG-590 and Omega 625DF50 alone, provide the greatest red signal transmission, while decreasing the spectral range of transmission, to levels lower than c. 730 nm and c. 670 nm, respectively (Table 3). We note additionally, that in testing for phosphorescence or other malign effects, the orientation or ordering of the filters had no observed effect on the transmission windows.

To demonstrate the combined effect of photomultiplier tubes and filter transmissions, the estimated quantum efficiencies (QE) for the PMTs of Figure 2a have been used. The QE at maximum wavelength for EMI 9635 PMT is 0.1% at 620 nm. Therefore, the effect of PMT quantum efficiency (QE) on signal transmission has been estimated, based on their efficiency at 620 nm, rather than at 710 nm or individual wavelengths. The estimated quantum efficiencies for the PMTs at 620 nm are ~ 0.1, 5 and 15% for the blue, green and red PMT's, respectively. As an example, the expected detection windows and intensities for the combination of Omega 625 DF50 and the three photomultipliers tested in this study are displayed in Figure 2c. A more detailed investigation is required to precisely quantify details of the transmission windows.

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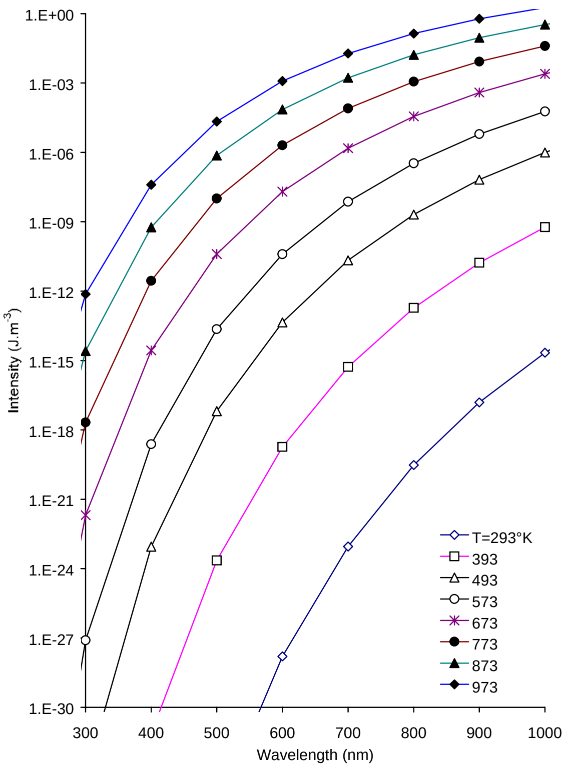

Figure 5.
Black body radiation obtained using Planck's law. The emission intensity of blackbody radiation plotted versus different wavelengths at temperatures shown.

Actual orange-red IRSL measurements using various filter and PMT combinations

In IRSL, the stimulation is generally thought to be a thermally–assisted photon process (Hütt et al., 1988). Increasing the sample temperature will increase the signal (Aitken, 1998). While increasing the sample temperature (for preheating or stimulation) has advantages including increasing the IRSL signal, it has a potential disadvantage of thermal incandescence. Thermal incandescence has previously hampered the application of red emission in thermoluminescence dating (e.g. Fattahi and Stokes, 2002a). Figure 5 shows the theoretical black body curves calculated from Planck's law. As can be seen in Figure 5, black body radiation increases with both substrate temperature and radiation wavelengths from 200 to 900 nm. The highest intensity of thermal incandescence (c. 10^{-2} J.m^{-3}) in TL studies will appear at ~ 500°C at 900 nm. In comparison, the intensity of typical 1W solid state infrared (830 ± 5 nm) laser

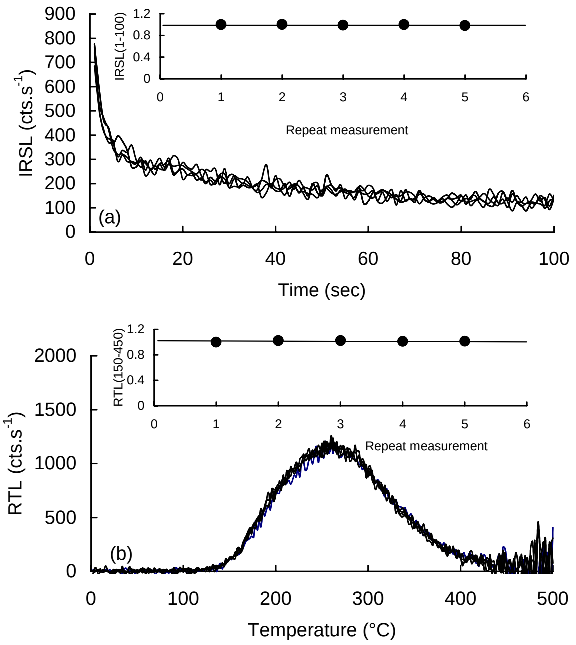

Figure 6.
*Orange-red IRSL and RTL reproducibility plot (from Fattahi and Stokes, 2002b). Orange-red IRSL and RTL of feldspar sample (lab No. 99/5/1 KF) was measured, respectively after giving a dose of ~ 1200 Gy. The procedure was repeated 5 times. (a) Repeated orange-red IRSL decay curves; inset shows total light sum of IRSL (0-100 sec) from individual curves versus measurement number. (b) Repeated RTL glow curves; inset shows total light sum of RTL (0-500°C) from individual curves versus measurement number. The detection system was EMI 9658 "red" PMT and OG 590 + FR 400S + 2*BG 39 filters*

diode unit is 400 mW.cm^{-2} (Bötter-Jensen et al., 2000). These data suggest that the effect of IR reflection originating from the IR source will be an order of magnitude greater than the effect of thermal incandescence as a background component.

To explore the effect of IR laser diode intensity on background, Fattahi and Stokes (2002b) examined a blank stainless steel disk while varying the laser intensity (0-100%). They demonstrated that there is a significant IR intensity-related background signal. While it is possible to minimize background generated thermally, a major problem is the transmission of the IR stimulation wavelength reflection from the sample.

To confirm the general patterns noted above we tested a range of filter combinations and PMT's using a potassium feldspar sample collected from a New Zealand Ignimbrite (sample 99/5/1) ***(Figure 6, Table 4).*** The sample was repeatedly given a 1200 Gy test dose and its orange-red IRSL and TL, respectively were measured, for a range of filter and PMT combinations (Fattahi and Stokes, 2002b). Orange-red IRSL measurements were made at 75°C for duration of 100 sec using IR intensity.

While there is at present no definitive choice, we consider the green PMT in combination with two FR 400S + BG 39 (1mm) plus OG 590 or RG 665 as an efficient arrangement for detecting the initial rapidly depleting portion of orange-red IRSL decay curves in either a broad orange-red (λ c. >600-720 nm) or far red (λ c. 665-720 nm) emissions, respectively. An Omega 625DF50 in combination with the green PMT is suitable in cases where details of the entire decay form and low background levels are required in near red (λ c. 600-660 nm) part of the spectrum. Alternatively, for very bright samples if neither the red or green PMT are available, an Omega 625DF50 or BG 39 + OG590 filters combined with a blue PMT may provide a usable combination for near red part of the spectrum. While this would result in a very low signal yield, it has the added advantage of not requiring active cooling.

Conclusion

Orange-red IRSL from feldspar is a potentially useful dosimeter for dating applications. We have evaluated a series of PMT and filter combinations to maximise orange-red IRSL measurements. We have modified a Risø model TA-15 automated TL/OSL reader. Modification consisted of two alternatives cooled PMT and a range of filter combinations which have not previously been employed in optical dating. Using either a cooled (~-20°C) extended Electron Tubes PMT S20, 9658 ("red") or an Electron Tube bialkaline, D716A PMT ("green") provides greater quantum efficiency in the red portion of the spectrum (600-750 nm) than a conventional blue-sensitive, 9635 bialkali PMT. A substantial disadvantage of using these 'red' and 'green' photomultiplier tubes however, is their relatively high quantum efficiency in the infrared. As a result, selection of a suitable filter combination is critical. There is strong evidence that the background is mainly due to the reflection of incident light, which is itself related to the intensity of IR from the IR laser diode (λ = 830 nm). To overcome the high background, we have attached and tested a variety of filter combinations. They included most of the available long cut filters and some long pass filters and one band pass filter. While, this reduces the transmission of IR to a low level, the red signal transmission also decreases. While all these PMTs are capable of measuring an orange-red IRSL signal, our data suggest that optimal

PMT	Limitation	Advantages
Blue: (Electron Tube 9635, bialkaline)	Low QE at red (0.1% at 630 nm)	Low QE at IR (<0.01% at 830nm)
Green: (Electron Tube D716A, bialkaline)	Med QE at red (2.5% at 630 nm) High Dark Noise (2000 c.s^{-1} at room temperature) - requires active cooling to decrease the Dark Noise one order of magnitude (~180 c.s^{-1}).	Med QE at IR (0.01% at 830 nm)
Red: (Electron Tube 9650, S20)	High QE at IR (2.5% at 830 nm) High Dark noise (2000 c.s^{-1} at room temperature) - requires active cooling to decrease the Dark Noise one order of magnitude (~200 c.s^{-1}).	High QE at red (15% at 630 nm)

Table 1.
Summary characteristics of the three-photomultiplier tubes used for detecting orange- red IRSL (λ c. 600-750 nm).

Filter type and thickness (mm)	Peak Transmission		IR Transmission		Heat and IR Rejection
	%	λ (nm)	%	λ(nm)	
Hoya HA-3 (3)	~ 80	340-620	>20	700->900	Poor
Schott BG-39 (2)	~ 80 ~ 60 ~ 30 ~ 8	450-530 540-580 580-620 620-640	~ 0.2	760-900	Good
Schott BG-39 (1)	~ 40 ~ 30 ~ 15	400-580 580-620 620-660	~ 0.5 ~ 0.1 ~ 0.1	700-720 720-760 860-900	Good
Corion FR – 400S (7)	~ 70 ~ 60 ~ 10	440-600 600-640 680-700	~ 2.0 ~ 0.5 ~ 0.3	700-720 720-740 760-900	Good
Omega 740 SP (2)	~ 85 ~ 80 ~ 60 ~ 20	510-580 460-625 420-680 410-720	~ 0.2 ~ 0.1 ~ 0.6 ~ 1.1	720-760 850-870 870-890 890-900	Medium
Delta SWP BL 685 (2)	~ 65 ~ 35 ~ 10	430-660 400-680 395-690	~ 0.1 ~ 0.1 ~ 0.3	700-750 850-880 880-900	Good
Omega 625DF50 (5)	~ 80 ~ 60 ~ 30	600-640 640-650 650-660	~ 0.1 ~ 0.2	860-880 880-900	Good

Table 2.
Spectral characteristics of some long cut filters

Filters	Max Peak Transmission %	λ (nm)	Min-Max Wavelength λ (nm)
FR-400S + OG-590	60	600-620	570-730
FR-400S + 2-63	52	610-630	580-730
FR-400S +2-61	46	630-650	600-730
FR-400S +3-67	46	570-620	550-730
FR-400S + RG 610	44	620-640	590-730
FR-400S + RG 665	25	670-680	645-730
BG-39 + OG-590	34	590-610	570-720
BG-39 +2-63	29	600-620	580-720
BG-39 +2-61	18	620-640	600-720
HA-3 + OG-590	60	610-630	530-900
BG-39 + RG 610	12	610-630	590-720
BG-39(1)+HA-3 + OG-590	20	580-600	560-720
BG-39(2)+HA-3 + OG-590	21	580-600	560-670
BG-39(1) + HA-3 + 2-63	12	600-620	580-710
BG-39(2) + HA-3 + 2-63	16	600-620	580-670
BG-39(1) + HA-3 + 2-61	8	620-640	600-710
BG-39(2) + HA-3 + 2-61	3	620-630	610-670
BG-39(1)+FR-400S+OG590	14	590-610	570-680
BG-39(2)+FR-400S+OG590	19	580-600	560-770
Omega 625DF50 (5)	80	600-640	590-660

Table 3.

Spectral characteristic of selected filters combination

Filter Combination	PMT	Blank SS BG at 90%	Back-ground (BG)	Signal (S)	S/N	Error S/N	S-BG
HA3+OG590	Blue	2 000.0					
SWP+OG590	Blue	30.0	70.4	91.1	1.29	±0.15	20.7
OM+OG 590	Blue	0.7	0.9	3.1	3.46	±1.11	2.2
FR+OG590	Blue	9.7	7.9	13.2	1.66	±0.33	5.2
BG39(2)+OG590	Blue	0.2	0.2	0.3	1.28	±0.64	0.1
OMEGA 625	Blue	0.7	0.7	2.5	3.80	±1.30	1.9
FR+FR+OG590+BG 39(1)	Blue	0.2	0.2	0.2	1.18	±0.65	0.0
SWP+OG590	Green	64.0	125.7	147.2	1.17	±0.12	21.5
OM+OG 590	Green	8.2	14.2	17.2	1.21	±0.22	3.0
FR+OG590	Green	8.0	11.9	15.4	1.30	±0.24	3.5
BG39(2)+OG590	Green	0.2	0.2	1.3	5.43	±2.33	1.1
OMEGA 625	Green	0.4	0.6	3.3	5.35	±1.82	2.7
BG39(1)+OG590	Green	2.4	3.2	5.6	1.75	±0.44	2.4
FR+FR+OG590	Green	0.5	0.7	3.0	4.45	±1.50	2.3
OM+FR+OG590	Green	0.0	1.4	4.0	2.79	±0.81	2.6
FR+Delta+OG 590	Green	0.4	0.4	1.3	2.96	±1.15	0.9
FR+ BG39(2)+OG 590	Green	0.2	0.2	1.1	4.71	±2.08	0.8
FR+FR+BG 39(1)+OG590	Green	0.2	0.3	1.6	4.76	±1.90	1.3
OM+FR+OG590	Red	110.0	123.3	142.8	1.16	±0.12	19.5
OM+FR+OMEGA 625	Red	3.0	29.3	33.6	1.15	±0.17	4.3
FR+BG39(2)+OG590	Red	3.0	3.1	8.5	2.78	±0.67	5.4
FR+BG39(1)+OG590	Red	50.0	43.6	63.0	1.44	±0.19	19.4
FR+FR+BG39(1)+OG590	Red	0.4	4.7	15.5	3.30	±0.70	10.8
BG39(1)+BG39(2)+ OG590	Red	11.0	10.3	14.6	1.42	±0.27	4.3
FR+BG39(1)+BG39(2)+ OG590	Red	0.4	0.5	1.2	2.29	±0.88	0.6

SWP = DELTA SWP 685 (18 mm dia); OM = Omega 750 SP; FR = Corion FR 400 S.

The units of ginal and background are counts per second ($cts.s^{-1}$) and shown by ($kcts.s^{-1}$)

Table 4.
Selected combinations of different filters and three blue, green and red PMTs (from Fattahi and Stokes, 2002b).

PMT/filter combination consist of either the green PMT + two FR 400S + BG 39 and OG 590 or RG 665 for wide red (600-720 nm) or far red (670-720 nm), respectively. The green PMT and an Omega 625DF 50 filter is the optimal combination for near red (λ c. 600-660 nm) emissions.

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